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Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies

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ABSTRACT

In this paper, the global market potential of solar thermal, photovoltaic (PV) and combined photovoltaic/thermal (PV/T) technologies in current time and near future was discussed. The concept of the PV/T and the theory behind the PV/T operation were briefly introduced, and standards for evaluating technical, economic and environmental performance of the PV/T systems were addressed. A comprehensive literature review into R&D works and practical application of the PV/T technology was illustrated and the review results were critically analysed in terms of PV/T type and research methodology used. The major features, current status, research focuses and existing difficulties/barriers related to the various types of PV/T were identified. The research methods, including theoretical analyses and computer simulation, experimental and combined experimental/theoretical investigation, demonstration and feasibility study, as well as economic and environmental analyses, applied into the PV/T technology were individually discussed, and the achievement and problems remaining in each research method category were described. Finally, opportunities for further work to carry on PV/T study were identified. The review research indicated that air/water-based PV/T systems are the commonly used technologies but their thermal removal effectiveness is lower. Refrigerant/heat-pipe-based PV/Ts, although still in research/laboratory stage, could achieve much higher solar conversion efficiencies over the air/water-based systems. However, these systems were found a few technical challenges in practice which require further resolutions. The review research suggested that further works could be undertaken to (1) develop new feasible, economic and energy efficient PV/T systems; (2) optimise the structural/geometrical configurations of the existing PV/T systems; (3) study long term dynamic performance of the PV/T systems; (4) demonstrate the PV/T systems in real buildings and conduct the feasibility study; and (5) carry on advanced economic and environmental analyses. This review research helps finding the questions remaining in PV/T technology, identify new research topics/directions to further improve the performance of the PV/T, remove the barriers in PV/T practical application, establish the standards/regulations related to PV/T design and installation, and promote its market penetration throughout the world.

Contents

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Nomenclature

A	heat transfer area (m^2)
A_c	collector aperture area (m^2)
C_b	thermal conductance of the bond between fin and tube (J/kg k)
C_p	heat capacity of flowing medium (J/kg k)
D_i	inside diameter of flow tubes (m)
D_o	outside diameter of flow tubes (m)
E_f	primary energy saving efficiency (%)
EPBT	Energy Payback Time
e	exergy (J/kg)
F	fin efficiency (%)
F'	fin efficiency factor
F_R	heat-removal factor
f	solar fraction
GPBT	Greenhouse-gas Payback Time
h	heat transfer coefficient (W/m^2 k)
I	incident solar radiation (W/m^2)
K	thermal conductivity of fin (W/m k)
$\dot{m}$	average mass flow rate (kg/s)
P_o	measured output power (W)
Q	energy (W)
t	temperature (°C)
U_L	overall heat loss coefficient (W/m^2 k)
W	distance between tubes (m)
Z	the reduction of annual GHG emission from the local power plant

Greek

α	absorptivity
β	temperature coefficient (/°C)
δ	thickness (m)
ξ	exergy efficiency (%)
η	efficiency (%)
Σ	embodied energy
τ	transmittance of the material
Ω	embodied GHG

Subscripts

a	air
ac	HVAC system
aux,e	auxiliary electricity required (W)
aux,t	auxiliary heat required (W)
bos	balance of system
c	ideal Carnot cycle
e	electricity
i	inlet
load,e	electric energy load (W)
load,t	Thermal energy load (W)
mtl	replacing building materials
o	overall
out	outlet
p,m	mean value of plate
power	conventional power plant
pv	PV
pvt	PV/T
r	equivalent radiation
th	thermal
u	useful
wm	work medium

1. Introduction

The global energy use has been steadily growing over the past 40 years and in 2008, the total annually consumed energy reached 474 exajoules (474×10^{18} J), of which 80–90% is from combustion of fossil fuels [1]. Despite the latest energy review [2] indicated that the world energy consumption was decreased by 1.1% in 2009 due to the unexpected global economic recession, energy consumption in several developing countries, particularly the fast-economy-growing Asia countries, still grow. Increased fossil fuel consumption has led to continuous rising carbon emission to the environment [3], which is thought to be the direct reason causing the global warming.

Solar thermal is currently providing only 0.5% of total primary energy need and solar photovoltaic (PV) has even lower energy supply ratio (0.04%) [4]. Both solar thermal and PV technologies have far high space to grow which

would be driven by the continuous technical advances and increased concerns of energy saving and environment protection. This development would certainly contribute to significant reduction of fossil fuel consumption and cut of carbon emission.

Solar thermal is one of the most cost effective renewable energy technologies and has huge market potential globally. It, representing more than 90% of the world-installed solar capacity, is utilized for various purposes including domestic hot water generation and space heating, solar assisted cooling and industrial process heating. The global solar thermal market has been continuously growing since the beginning of the 1990s and in Europe, solar thermal market was tripled from 2002 to 2006 and still in booming. A vision plan issued by European Solar Thermal Technology Platform (ESTTP) indicated that by 2030 up to 50% of the low and medium temperature heat will be delivered through solar thermal [5]. The European Solar Thermal Industry Federation (ESTIF) has predicted that by 2020, the EU will reach a total operational solar thermal capacity of between 91 and 320 giga-Watts (GW), thus leading to saving of equivalent to at least 5,600 tonnes crude oil. By 2050, the EU will eventually achieve 1,200 GW of solar thermal capacity [6].

PV is currently a technically and commercially mature technology able to generate and supply short/mid-term electricity using solar energy. Although the current PV installations are still small and provide only 0.1% of world total electricity generation, a market review indicated that the global PV installations are growing at a 40% average annual rate [7]. With continuous technical advance, increased installation volume, reduced price and encouraging legal policies, PV will certainly continue on the fast-growing pace and eventually become an important energy supplier in the world. It is predicted by IEA at its recent Technology Roadmap – Solar Photovoltaic Energy that PV will deliver about 5% of global power need by 2030 and 11% by 2050. The accelerated use of PV will result in more than 100 giga-tonnes (Gt) of CO_2 emission reduction during the period of between 2008 and 2050 [7].

PV/T is a hybrid technology combining PV and solar thermal components into a single module to enhance the solar conversion efficiency of the module and make economic use of the space. A PV/T module can simultaneously generate electricity and heat, and therefore takes advantages of both PV and solar thermal technologies. The dual functions of the PV/T result in a higher overall solar conversion rate than that of solely PV or solar collector, and thus enable a more effective use of solar energy. Its market potential is therefore expected to be higher than individual PV and solar thermal systems. However, since the PV/T is a recently emerging technology, various issues relevant to PV/T, e.g., current technical status, difficulties and problems remaining, market potential and barriers in practical application, etc, still remain unclear. To clear up these matters, a review study into the current works on PV/T technology is most needed. The work will have significant global impacts in terms of several important aspects, namely (1) helping engineers/professionals to understand the basic knowledge of PV/T, identify the technical feature of the PV/T systems, and select, design, install and evaluate PV/T system; (2) helping academia/researchers to identify research directions/topics relevant to PV/T technology; (3) helping policy makers and governmental officers to deliver the strategic plans related to PV/T and establish the associated standards and regulations; and (4) helping industry to identify the barriers of PV/T in piratical application, develop the commercially viable PV/T products, and establish the associated market exploitation plan to promote wide application of PV/T technology across the world.

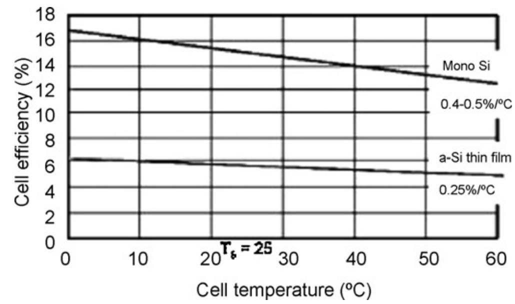

Fig. 1. Established efficiency-to-tempereature relationship.

2. Basic concept and theory, classification and performance evaluation standards relative to the PV/T technology

2.1. Basic concept of the PV/T and theory behind the PV/T operation

PV cells/modules are well known solar electricity generating components and the solar efficiency of the PVs is a parameter associated with the cells' materials and temperature. In general, the PVs' electrical efficiency is in the range 6–18%, which is a value measured at the Nominal Operating Cell Temperature (NOCT) (0.8 kW/m^2 of solar radiation, 20 °C of ambient temperature, and 1 m/s of wind speed) [8]. It is well known that the solar electrical efficiency of the PV cells falls with the rise of its operating temperature, as shown in Fig. 1. Increasing the temperature of PV cells by 1 K leads to about 0.4–0.5% reduction of the electrical efficiency for the crystalline silicon based cells [9,10] and around 0.25% for the amorphous silicon (a-Si) cells [11].

To increase electrical efficiency of the PVs and make good use of the incident solar radiation, it is most desired to remove the accumulated heat from the concealed PV surface and use this part of heat appropriately. The PV/T is a technology developed for this purpose which combines the PV cells/modules and heat extraction components into a single module. This allows cooling of the PV cells leading to increased PVs' electrical efficiency and in the meantime, simultaneously utilizing the extracted heat for heating purpose. By doing so, the PV/T solar collector can obtain the enhanced overall solar efficiency and thus provide a better way utilizing solar energy. The PV/T, merging PVs into the solar thermal module, represents a new direction for renewable heating and power generation. Fig. 2 indicates the inter-relationship among different solar conversion technologies.

A typical PV/T module is a sandwiched structure comprising several layers, namely from the top to bottom, a flat-plate thermally clear covering as the top layer; a layer of photovoltaic cells or a commercial PV lamination laid beneath the cover with a small air gap;

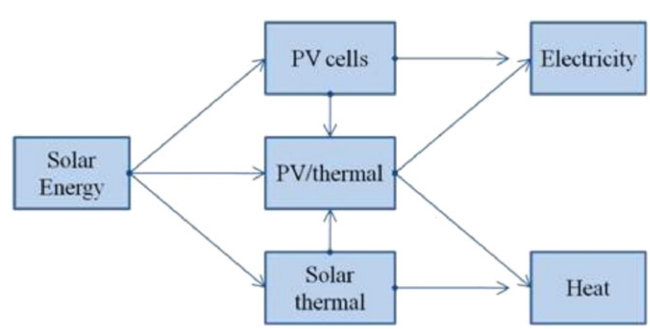

Fig. 2. Network of different solar conversion technologies.

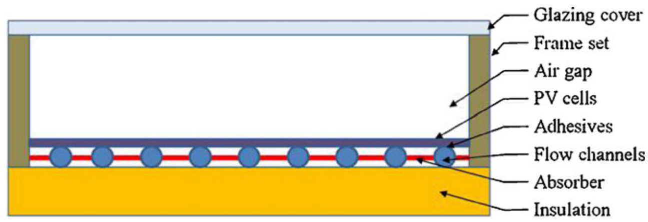

Fig. 3. A focused cross section of typical PV/T module.

tubes or flowing channels through the absorber and closely adhered to the PV cell layer; a thermally insulated layer located right below the flow channels. All the layers are fixed into a framed module using the adequate clamps and connections. Fig. 3 is a schematic of a typical PV/T module structure.

The general concept of the PV/T was originally addressed by Kern and Russell [12] in 1978. For a PV/T module, the solar irradiation with the wavelength from 0.6 to 0.7 μm is absorbed by the PV cells and converted into electricity, while the remaining irradiation is mostly transformed in form of thermal energy. The PV/T module can collect solar energy at different grades (wavelengths) and consequently lead to an enhanced energy and exergy efficiency [13]. According to Zongdag et al. [13] and Zhao et al. [14], the PV/T module could collect and convert higher percentage of solar energy than either an individual PV panel or thermal collector do at the same absorbing area and therefore, offers a potential creating a low cost and highly effective solution for heat and power generation.

A PV/T module is basically derived from the combined functions of a flat-plate solar (thermal) collector and of a photovoltaic panel. The overall efficiency is sum of the collector's thermal efficiency η_{th} and the PVs' electrical efficiency η_e, which are defined as the ratios of useful system heat gain and electricity gain to the incident solar irradiation striking on the collector's absorbing surface, and is written as follow:

$$\eta_o = \eta_{th} + \eta_e \tag{1}$$

2.1.1. Thermal efficiency of the PV/T collector (η_{th})

The thermal efficiency (η_{th}) of a flat-plate PV/T collector is a ratio of the useful thermal energy, Q_u, to the overall incident irradiation, I, and can be written as:

$$\eta_{th} = \frac{Q_u}{I} \tag{2}$$

The heat collected by the flat-plate PV/T collector could either be given as the coupling result of average mass flow rate ($\dot{m}$), heat capacity of flowing medium (C_p) and temperature difference of the medium at the collector inlets (t_i) and outlets (t_o), as below:

$$Q_u = \dot{m}C_p(t_{out} - t_i) \tag{3}$$

Or it could be simply expressed by the difference of absorbed solar radiation, heat loss and produced electrical energy:

$$Q_u = A_c[I(\tau\alpha) - U_L(t_{p,m} - t_a) - Q_e] \tag{4}$$

where, A_c is the collector area; $(\tau\alpha)$ is transmittance-absorption effort of glazing cover; U_L is the overall thermal loss efficient; t_a is the average air temperature; Q_e is the electrical energy generated from the PVs. The parameter $t_{p,m}$, representing the mean absorber plate temperature, is difficult to measure or calculate since it is a complex function of different collector designs, incident solar radiation and working medium properties. To allow analysis, the equations for a flat-plate solar collector is modified by the Hottel and Whillier [15] using the fluid inlet temperature (t_i) to replace the mean absorber temperature ($t_{p,m}$), which has been widely used in the design and evaluation of solar air and liquid collectors. It should be addressed that the equations are correlated to the solar

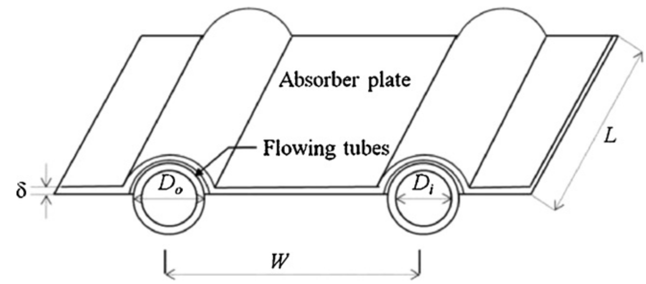

Fig. 4. Schematic of an absorber plate showing the various dimensions.

collector configuration as shown in Fig. 4. If the configuration of the collector is changed, some geometrical parameters in the equations may vary correspondingly, while the basic work principle of the collector remains same.

$$Q_u = F_R A_c[I(\tau\alpha) - U_L(t_i - t_a) - Q_e] \tag{5}$$

where, F_R is the heat-removal factor which is connected with the efficiency factor (F') using the following equation:

$$\frac{F_R}{F'} = \frac{IC_p}{U_L F'}\left[1 - \exp\left(-\frac{U_L F'}{IC_p}\right)\right] \tag{6}$$

where, F' varies with different types of working mediums (e.g., water or air):

$$F' = \frac{1/U_L}{W[1/U_L[D_o + (W - D_o)F] + 1/C_b + 1/\pi D_i h_{wm}]} \text{ for water} \tag{7}$$

$$F' = \frac{1}{1 + [U_L/(h_{wm}A/A_c + 1/(1/h_r + 1/h_{wm})]} \text{ for air} \tag{8}$$

where, W is the distance between tubes; D_o and D_i are the outside and inside diameter of flow tubes; C_b is conductance of the bond between the fin and tube; h_{wm} is the heat transfer coefficient of working medium; A/A_c is the ratio of heat transfer area to collector aperture are; h_r is the equivalent radiation coefficient; F is the fin efficiency, which could be given by:

$$F = \frac{\tanh[\sqrt{(U_L/k\delta)}(W - D_o/2)]}{\sqrt{(U_L/k\delta)}(W - D_o/2)} \tag{9}$$

where, k is the thermal conductivity of the fin and δ is the fin thickness.

2.1.2. The electrical efficiency of the photovoltaic modules (η_e)

The electrical efficiency (η_e) of a PV module is the ratio of measured output power (P_o) to the overall incident solar radiation.

$$\eta_e = \frac{P_o}{IA_c} \tag{10}$$

It is known that the electrical efficiency of the PV module decreases with the increase of the cells' working temperature and this dependence can usually be written as [16]:

$$\eta_e = \eta_{rc}[1 - \beta_{PV}(t_{PV} - t_{rc})] \tag{11}$$

where, η_{rc} is the initial electrical efficiency at reference temperature; β_{PV} is the cell efficiency temperature coefficient; t_{pv} and t_{rc} are respectively the PV cell temperature and its reference temperature. The generated electrical energy can be calculated as follows:

$$Q_e = P_o = \eta_e I A_c \tag{12}$$

2.2. Classification of the PV/T modules

PV/T modules could be structurally and functionally very different. In terms of coolant used, the modules could be classified as

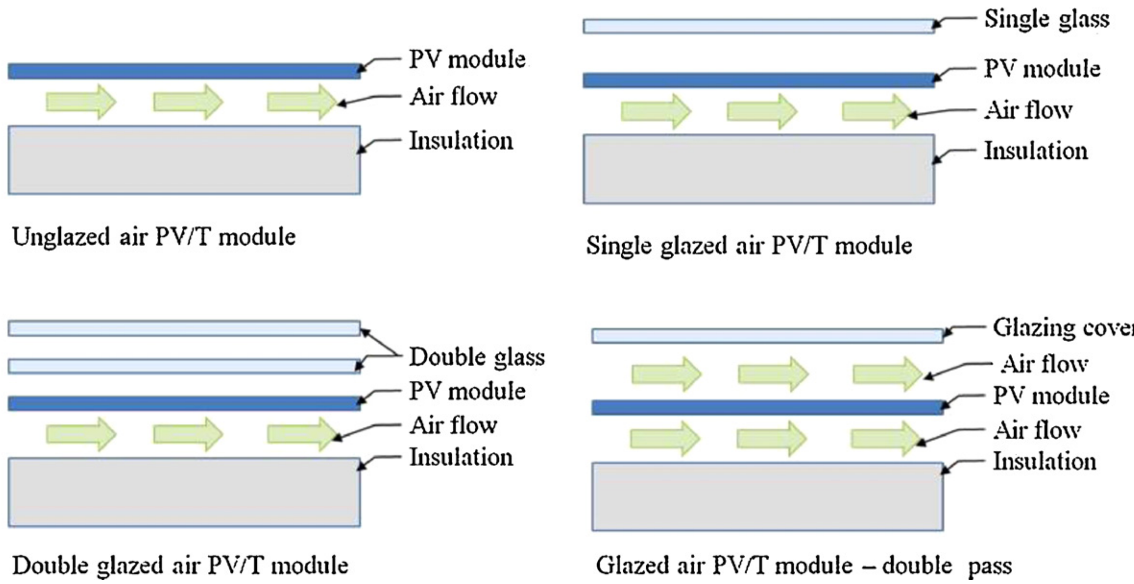

Fig. 5. Cross sections of air based PV/T modules.

air, water, refrigerant and heat-pipe fluid based types. In terms of the physical structure applied, the modules could be classified as flat plate, concentrated and building integrated types. In this section, the coolant based classification was adopted and illustrated as follows:

2.2.1. Air-based PV/T

An air-based PV/T module is a solar air heater with an additional PV layer laminated on the top or bottom of the naturally or mechanically ventilated air channels. This PV/T type could be formulated by incorporating an air gap between the PV modules' back surface and the building fabric (facade or tilted roof). Usually, this type of PV/T module is designed for the end-users who have demand in hot air, space heating, agriculture/herb drying or increased ventilation, as well as the electricity generation. For this type of module, air could be delivered from above, below or on both side of the PV absorber, as shown in Fig. 5.

2.2.2. Water-based PV/T

A water-based PV/T module, as shown in Fig. 3, has a similar structure as the conventional flat-plate solar collectors. The absorber is attained with numerous PV cells that are series or parallel connected and fixed with a serpentine or a series of parallel tubes underneath. Water is forced to flow across the tubes and if the water temperature remains lower, the PV cells will be cooled, thus leading to the increased electrical efficiency. In the meantime, the passing water will be heated by absorbing the PV heat and will be delivered to certain heat devices to provide heating. This part of water may be consumed; or alternatively cooled in the heating services and flows back the module to regain heat. Compared to the air-based system, the water-based PV/T systems could achieve the enhanced cooling effectiveness due to higher thermal mass of water over the air and therefore both the thermal and electrical efficiencies of the systems would be higher. Zondag et al. [17] addressed several water flow patterns in the PV/T, namely, sheet and tube, channel,

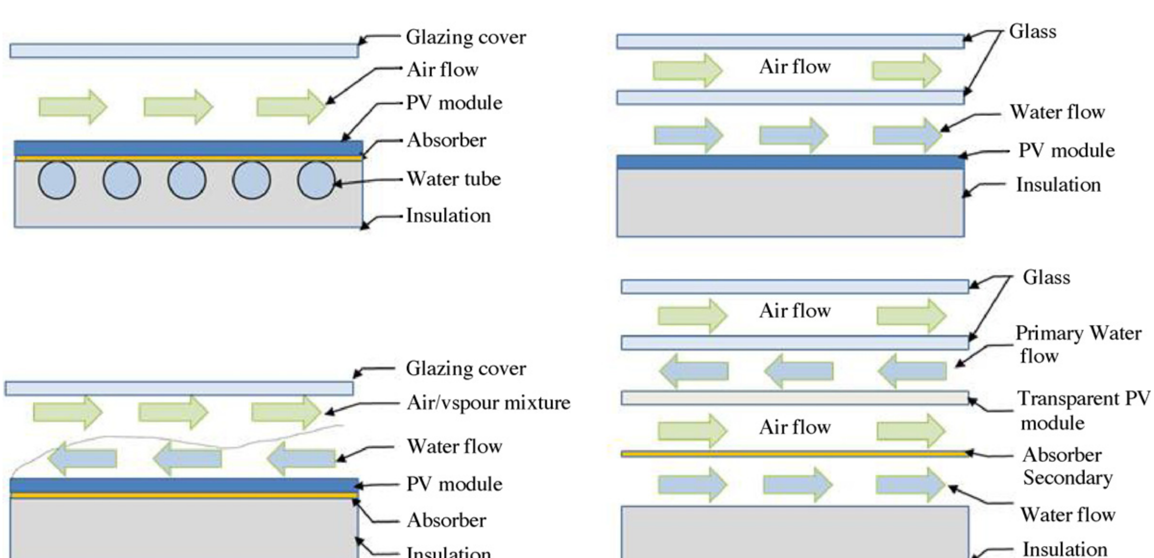

Fig. 6. Types of water PV/T collectors.

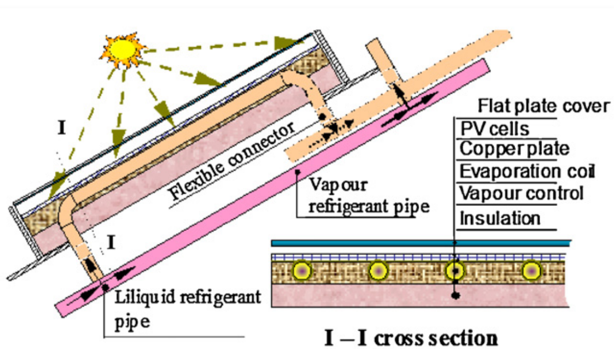

Fig. 7. Cross-section view of the PV evaporator roof panel [14].

free flow and two absorber types, which are shown schematically in Fig. 6.

2.2.3. Refrigerant-based PV/T

In recent years, refrigerant-based PV/T heat pump systems have been studied. Kern and Russell [12] initially proposed a simple PV/T collectors connected with heat pump systems, and studied their energy saving and economic benefits. Recent study suggested a novel concept of PV/T module for heat pump application. This module lays the direct expansion evaporation coils underneath the PV modules which allow a refrigerant to be evaporated when passing through the modules. In this way, the coils would act as the evaporation sector of the heat pump, which would allow the refrigerant to evaporate at a very low temperature, e.g., 0–20 °C. As a result, the PV cells would be cooled to a similar low temperature, which would result in significant increase in the panels' heat and electrical efficiencies. The compressor in the heat pump would increase the pressure of the vapour generated from the panels and deliver it to the condenser to provide heating. In operation, the compressor would be driven by the PV generated electricity, thus creating a solar powered heat pump independent of fossil fuel energy. Fig. 7 gives a cross-sectional view of a glazed PV evaporator roof panel [14], and Fig. 8 is the schematic of the PV/T based heat pump system [14].

2.2.4. Heat-pipe-based PV/T

Heat pipes are considered efficient heat transfer mechanisms that combine the principles of both thermal conductivity and phase transition. A typical heat pipe, as indicated in Fig. 9, consists of three sections namely, evaporated section (evaporator), adiabatic section and condensed section (condenser), and provides an ideal solution for heat removal and transmission.

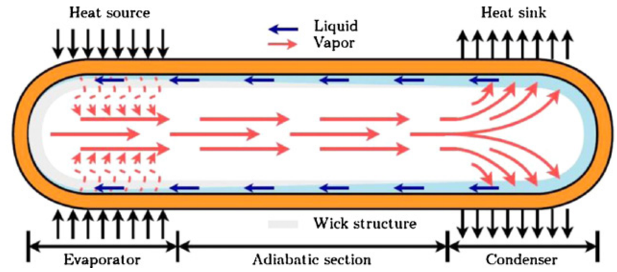

Fig. 9. Schematic of a conventional heat pipe [18].

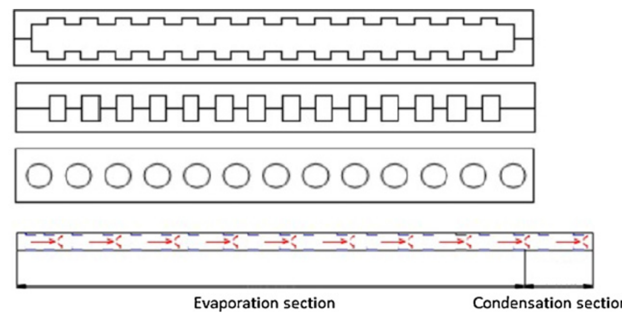

Fig. 10. Schematic of three types of flat-plat heat pipes with micro-channel array [19].

PV/heat-pipe combination has been recently studied. Zhao et al. [19–21] proposed a PV/flat-plate-heat pipes array for co-generation of electricity and hot air/water. This prototype module comprises a photovoltaic layer and a flat plate heat pipe containing numerous micro-channel arrays acting as the evaporation section of the heat pipes. The other end of the heat pipe is the condensation section which releases heat to the passing fluid and the fluid within the section is condensed owing to the heat discharge. He claimed that the flat-plate geometry is more efficient due to the excellent thermal contact between the PV cells and heat extraction devices, which results in a smaller thermal resistance and higher overall solar conversion efficiency. In this way, the PV efficiency could increase by 15–30% compared to the sole PVs, if its surface temperature is controlled to around 40–50 °C. The overall solar conversion efficiency of the module was around 40%. Figs. 10 and 11 show schematically three types of PV/heat-pipe modules acting as the thermal and power co-generation units.

Qian et al. [22,23] brought forward a new concept for building integrated photovoltaic/thermal system utilizing oscillating heat pipe. This system is designed as the facade-assembled components

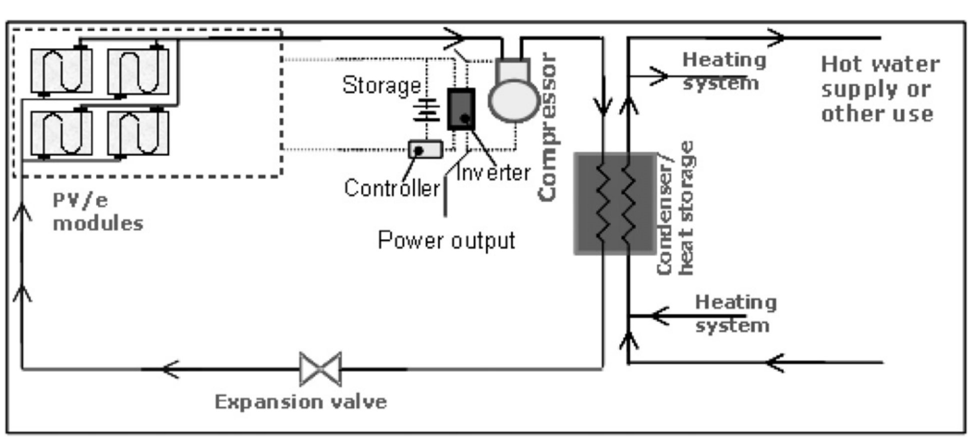

Fig. 8. Schematic of the PV/e roof module based heat pump and micro-generation system [14].

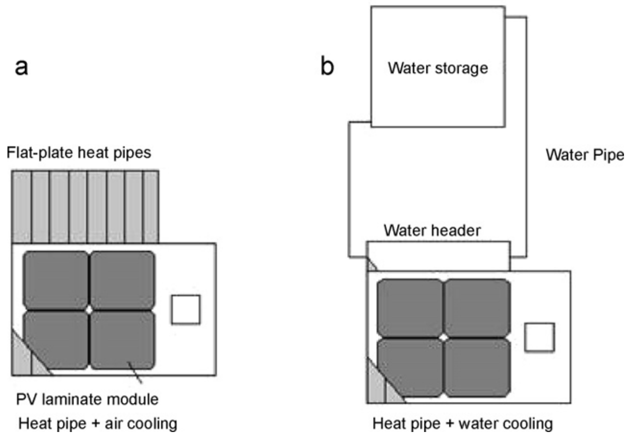

Fig. 11. Schematic of a PV/flat-plate heat pipe: (a) air cooling; (b) water cooling [21].

to transport heat from the concealed PV cells (OHP-BIPV/T), as shown in Fig. 12. The system consists of the oscillating heat pipes, headers, finned tube, graphite conductive layer, metal frame, PV laminate module and insulations. When in operation, the working fluid within the metal heat pipes will absorb heat from the PV cells and be evaporated into vapour fluid. The vapour will flow up into the finned tube where it is condensed by releasing heat to the passing fluid and returns back to the absorber by effect of gravity and capillary forces.

2.2.5. General comparison of the currently available PV/T types and their technical characteristics

A general comparison of the four currently available PV/T types was made in terms of their technical characteristics, as indicated in Table 1. The overall module efficiencies for different PV/T types were calculated on the basis of the same external solar/weather conditions (i.e. typical weather condition on 22nd December in mid-east area of UK) and operational conditions (i.e. 0.01 kg/m^2 s of mass flow rate, 10% of initial PV efficiency). The calculation models used are (1) Indoor-simulator (IS) model for air-based PV/T [24]; (2) Integrated PV/T system (IPVTS) model for water-based PV/T [25]; (3) PV solar assisted heat pump (PV-SAHP) model for refrigerant-based PV/T [26]; and (4) PV/flat-plate heat pipe (PV/FPHP) model for heat-pipe-based PV/T [20]. It is seen that the air- and water-based PV/Ts are riskless and lower cost and therefore, considered to be more practical systems for application. The refrigerant-based PV/T has the advantage of low/steady working temperature which could significantly improve the system's solar conversion efficiency;

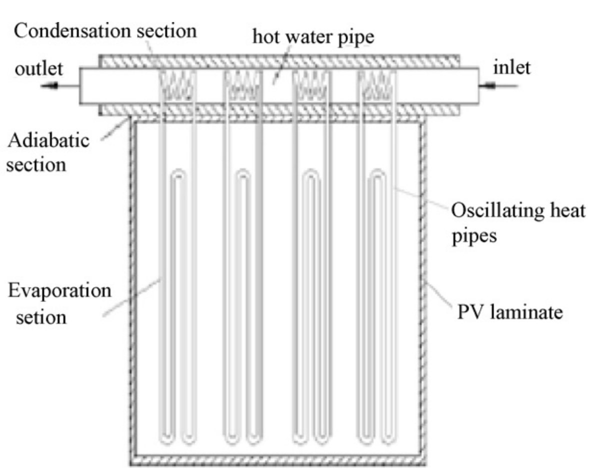

Fig. 12. The schematics of OHP-BIPV/T module [22].

whereas the heat-pipe-based PV/T can extract heat from PV cells instantly and if the operating temperature of the heat pipe fluid can be adequately controlled, the solar efficiency of the system could be significantly improved. However, these four systems have also found their own disadvantages that are addressed in Table 1. To summarise, air type has poor heat removal performance due to its low thermal mass and less organised air flow; water type remains increasingly growth of water temperature and fall in solar efficiency due to variation of the water temperature over the operational period and at high temperature operation, the heat removal effectiveness is becoming very poor; refrigerant type is difficult to handle in operation as pressurisation and depressurisation are required in different parts of the system, and risks of leakage and unbalanced refrigerant distribution remain high during the whole process; finally the heat pipe type retains the cost problem that may affect its wide deployment in practical projects.

2.3. Performance evaluation standards

Several national/regional standards are currently available for evaluating performance of solely arranged solar thermal and PV devices. For solar thermal, the available standards include EN 12975 [27,28], EN 12976 [29,30], EN 12977 [31–35], Solar Keymark [36], ISO 9806 [37–39], MCS 004 [40] and other national solar thermal themes; for PV, standards including IEC (61215, 61646, 61730) [41–44], UL (1703, 1741 and 4703) [45–47], IEEE (1262 and 929) [48,49], CE-marking [50] and other national electric codes, are in place. No published legal standards were found to address the performance issues of the PV/T. Instead, the methods for evaluating the PV/T were suggested in several academic papers. To summarise, the technical performance of the PV/T systems is usually evaluated using several indicative parameters including overall energy efficiency, overall exergy efficiency, primary-energy-saving efficiency, and solar fraction. The economic performance of the PV/T systems is measured with Life Cycle Cost (LCC) and Cost Payback Time (CPT), and the environmental benefit of the system is justified using the Energy Payback Time (EPBT) and Greenhouse Payback Time (GPBT). These parameters are briefed as below:

2.3.1. Technical performance evaluation parameters

2.3.1.1. Overall energy efficiency. Overall energy efficiency is the ratio of collected electrical and heat energy to incident solar radiation striking on the PV/T absorber. It is yielded from the first law of thermodynamics and indicates the percentage of the energy converted from the solar radiation. In a PV/T module, the electrical efficiency is much lower than the thermal efficiency and therefore the overall energy efficiency will largely rely on the thermal energy conversation of the system. It should be pointed out that the overall energy efficiency ignores the difference between heat and electrical energy in terms of the energy grade (quality) and therefore, is inadequate to fully justify the energy performance of the PV/T systems.

2.3.1.2. Overall exergy efficiency. Overall exergy efficiency takes into account difference of energy grades between heat and electricity and involves a conversion of low grade thermal energy into the equivalent high grade electrical energy using the theory of Carnot cycle. The overall exergy (e_o) of the PV/T could be written as follow:

$$e_o = e_{th} + e_e = (\xi_{th} + \xi_e)I = \xi_o I \quad (13)$$

where, e_{th} *and* e_e are the thermal and electrical exergy respectively; ξ_{th} and ξ_e are the thermal and electrical exergy efficiency; ξ_0 is the overall exergy efficiency.

The thermal exergy could be further written as:

$$e_{th} = \eta_c Q_u = \eta_c \eta_{th} I = \xi_{th} I \quad (14)$$

Table 1
The characteristics comparison of different heat extraction methods.

PV/T models	Average efficiency (%)	Advantage	Disadvantages
'IS' model for air based PV/T type [24]	24–47	Low cost Simple structure	Low thermal mass Large air volume Poor thermal removal effectiveness High heat loss
'IPVTS' model for water based PV/T type [25]	33–59	Low cost Direct contribution High thermal mass Low flow volume	Still-high PV temperature Unstable heat removal effectiveness Complex structure Possible piping freezing
'PV-SAHP' model for refrigerant based PV/T type [26]	56–74	Low PV temperature Stable performance High efficiency Effective heat removal	Risk of leakage Unbalanced liquid distribution High cost Difficult to operate
'PV/FPHP' model for heat pipe based PV/T type [20]	42–68	Low PV temperature Stable performance High solar efficiency Effective heat removal Reduce power input	High cost Risk of damage Complex structure

where, η_c is the ideal Carnot efficiency [51]:

$$\eta_c = \left(1 - \frac{293\ \mathrm{K}}{293\,\mathrm{K} + (t_{wm} - t_a)}\right) \tag{15}$$

where, t_{wm} is the final temperature of the work medium.

The electrical exergy is written as:

$$e_e = \eta_e I = \xi_e I \tag{16}$$

The overall exergy efficiency could be written as:

$$\xi_o = \eta_c \eta_{th} + \eta_e \tag{17}$$

The exergy efficiency has considered the energy grade difference between the heat and electricity and therefore, is a more rational index to evaluate performance of the PV/T systems.

2.3.1.3. The primary-energy saving efficiency. Huang et al. [25,52] proposed another performance evaluation method to recognise the energy grade difference between heat and electricity namely, the Primary Energy Saving Efficiency (E_f), which is given by:

$$E_f = \frac{\eta_e}{\eta_{power} + \eta_{th}} \tag{18}$$

where, η_{power} is the electrical power generation efficiency for a conventional power plant which is considered 0.38. For simplicity, the efficiency of conventional heating systems is considered 100% which is achievable if a condensing boiler is used. Huang [25] suggested that Primary-Energy Saving Efficiency of a PV/T system should be higher than 0.50, in order to compete a pure solar hot water system.

2.3.1.4. Solar fraction. From the primary-energy saving point of view, solar fraction (f) can also be used to evaluate the performance of PV/T system. It is defined as the fractional ratio of primary energy saving that a PV/T system can obtain to the overall energy demand, and could be written as:

$$f = \frac{1}{2} \times \left(\frac{Q_{load,t} - Q_{aux,t}}{Q_{load,t}} + \frac{Q_{load,e} - Q_{aux,e}}{Q_{load,e}}\right) \tag{19}$$

where, $Q_{load,t}$ and $Q_{aux,t}$ is the overall thermal load and auxiliary heat required; $Q_{load,e}$ and $Q_{aux,e}$ is the total electrical load and auxiliary electricity needed. Kalogirou [53] indicated that the solar fraction is lower in the winter months and higher in the summer months reaching an annual value of 0.49 for a hot water supply system.

To summarise, the energy and exergy efficiency are the major performance evaluation indexes for PV/T systems; whereas the primary-energy saving efficiency and solar fraction are occasionally used to evaluate the fossil fuel saving capacity of the PV/T systems. In reality, different end-users have different energy demands that would somehow affect performance of the PV/T systems in use. Choosing an appropriate evaluation method for a specific PV/T installation would need to take both energy supply and demand into consideration.

2.3.2. Economical and environmental measures of the PV/T systems

In terms of economic measures of the PV/T, Tripanagnostopoulos et al. [54] suggested the life cycle cost assessment method which takes into account the capital cost of system installation and associated operational and maintenance cost over the system's life cycle. The time related issues such as inflation, tax and/or company discount rates should also be the factors to be considered [55]. A simplified approach for assessing PV/T's economic value is by using Cost Payback Time (CPBT, in year) which ignores the time relevant items and maintenance cost and therefore is inaccurate. Table 2 details the cost breakdown/payback issues related to various types of PV/T installations.

For environmental measures, two payback items, the Energy Payback Time (EPBT) and the Greenhouse-gas Payback Time (GPBT), can be applied. EPBT is the ratio of the embodied energy for the PV/T and its annual energy output. Embodied energy refers to the quantity of energy required to produce the PV/T in its production phase. Chow [55] suggested the mathematic expressions of the EPBT and GPBT for the PV/T system as below:

$$\mathrm{EPBT} = \frac{\Sigma_{pvt} + \Sigma_{bos} - \Sigma_{mtl}}{E_{pv} + E_{th} + E_{ac}} \tag{20}$$

where, Σ_{pvt}, Σ_{bos} and Σ_{mtl} are the embodied energy of the PV/T system, the balance of system and the replacing building materials; E_{pv} is the annual useful electricity output; E_{th} is the annual useful heat gain (equivalent), and E_{ac} is the annual electricity saving of HVAC system due to thermal load reduction.

$$\mathrm{GPBT} = \frac{\Omega_{pvt} + \Omega_{bos} - \Omega_{mtl}}{Z_{pv} + Z_{th} + Z_{ac}} \tag{21}$$

where, Ω represents the embodied GHG (or CO_2 equivalent) and Z is the reduction of annual GHG emission from the local power plant owing to the PV/T operation. The environmental measures of the selected PV/T installations are given in Table 3 [54].

Table 2
Cost breakdown and cost payback time of all systems studied [54].

System cost 30 m^2 installation cost payback time (CPBT)	Cost of PV + HRU + REF (€)	Cost of electrical + thermal bos (€)	Installation cost (€)	Total cost (€)	CPBT for electricity saving (in yr)	CPBT for electricity and gas saving (in yt)
PV	21,000	1500	1500	2400	25.8	25.8
PV + REF	22,500	1500	1500	25,500	22.9	24.1
PV-TILT	21,000	1500	900	23,400	22.9	26.9
PVT/UNGL-25 °C	24,000	4500	1500	30,000	11.9	18.1
PVT/UNGL-35 °C	≫	≫	≫	≫	18.7	23.8
PVT/UNGL-45 °C	≫	≫	≫	≫	28.1	29.6
PVT/UNGL + REF-25 °C	25,500	4500	1500	31,500	11.1	17.22
PVT/UNGL + REF-35 °C	≫	≫	≫	≫	17.0	22.3
PVT/UNGL + REF-45 °C	≫	≫	≫	≫	25.5	28.1
PVT/GL-25 °C	27,000	4500	1500	33,000	10.5	17.6
PVT/GL-35 °C	≫	≫	≫	≫	14.5	21.9
PVT/CJL-45°C	≫	≫	≫	≫	21.2	27.9
PVT/GL + REF-25 °C	28,500	4500	1500	34,500	10.3	17.2
PVT/GL + REF-35 °C	≫	≫	≫	≫	13.9	21.1
PVT/CL + REF-45 °C	≫	≫	≫	≫	19.8	26.3
PVT/UNGL + TILT-25 °C	24,000	4500	900	29,400	11.8	18.2
PVT/UNGL-TILT-35 °C	≫	≫	≫	≫	18.5	24.2
PVT/l.1NGL-TILT-45 °C	≫	≫	≫	≫	28.2	30.8
PVT/GL-TILT-25 °C	27,000	4500	900	32,400	10.5	17.9
PVT/GL-TILT-35 °C	≫	≫	≫	≫	14.2	22.1
PVT/GL-TILT-45 °C	≫	≫	≫	≫	20.7	28.2

3. R&D progress and practical application of the PV/T technologies

3.1. Overview of PV/T related R&D works

Large quantity of research works have been carried out to study the performance of various types of PV/T configurations, optimize their geometrical sizes and suggest the favourite operational parameters related to the PV/T. As the result, many useful results and conclusive remarks have been obtained and these are selectively indicated as follows:

Hendrie [56] developed a theoretical model for the flat plate PV/T solar collectors and by using the model, he carried out study into the thermal and electrical performance of an air and a liquid based PV/T solar collector. He concluded that when the PV modules were not in operation, the air and liquid based collectors could achieve the peak thermal efficiencies of 42.5% and 40% respectively. However, when the PV modules were in function, the air and liquid based units obtained slightly lower thermal efficiencies which are 40.4% and 32.9% respectively. The measured peak electrical efficiency of these units was 6.8%.

Florschuetz [57] used the well know Hottel–Whillier [15] thermal model for the flat plate solar collectors to analyse the performance of the combined PV/T collector. By slightly modifying the parameters existing in the original computer program, the model became available for analysing the dynamic performance of the PV/T collector. Assuming that the solar PVs' electrical efficiency is linearly reduced when the cells' temperature increases, the thermal and electrical efficiencies of the combined PV/T collector were obtained and the results are further analysed to established the correlations between the efficiencies and various operational parameters of the collectors.

Raghuraman [58] developed two one-dimensional analytical models to predict the thermal and electrical performance of both liquid- and air-based flat-plate PV/T collectors. The analyses took into account the difference of temperature of the primary absorber

Table 3
EPBT and CO_2 PBT values for all systems studied [54].

System EPBT and CO_2PBT results	EPBT for replacing electricity only (yr)	CO_2 PBT for replacing electricity only (yr)	EPBT for replacing electricity and gas (yr)	CO_2 PBT for replacing electricity and gas (yr)
PV	2.9	2.7	2.9	2.7
PV + REF	2.7	2.5	2.7	2.5
PV-TILT	3.2	3.1	3.2	3.1
PVT/UNGL-25 °C	1.0	0.9	1.2	1.5
PVT/UNGL 35 °C	1.9	1.7	2.2	2.4
PVT/UNGL-45 °C	3.6	3.3	3.8	3.7
PVT/UNGL + REF-25 °C	0.9	0.9	1.2	1.4
PVT/UNGL + RBF-3i5 °C	1.7	1.5	2.0	2.2
PVT/UNGL + REF-45 °C	3.1	2.9	3.4	3.4
PVT/GL-25 °C	0.8	0.8	1.1	1.3
PVT/GL-35 °C	1.3	1.2	1.6	1.9
PVT/GL-45 °C	2.2	2.0	2.6	3.0
PVT/GL + REF-25 °C	0.8	0.8	1.0	1.3
PVT/GL + REF-35 °C	1.2	1.1	1.5	1.8
PVT/GL + REF-45 °C	2.0	1.9	2.4	2.7
PVT/UNGL-TILT-25 °C	1.0	1.0	1.3	1.6
PVT/UNGL-TILT-35 °C	1.9	1.8	2.3	2.5
PVT/UNGL-TILT-45 °C	3.8	3.5	4.1	4.1
PVT/GL-TILT-25 °C	0.8	0.8	1.1	1.4
PVT/GL-TILT-35 °C	1.3	1.2	1.6	2.0
PVT/GL-TILT-45 °C	2.2	2.0	2.7	3.1

(the PV cells) and secondary absorber (a thermal absorber flat plate) and a number of design notes were recommended to enable maximized energy utilization of the collectors.

Bergene and Lovvik [59] developed a dedicated PV/T mathematical model and the associated algorithms enabling quantitative predictions of the performance of the system. The model was established on analysis of energy transfers including conduction, convection and radiation initiated by Duffie and Beckman [16], and the results of model operation suggested that the overall efficiency of PV/T collectors are in the range 60–80%.

Sopian et al. [60] developed the steady-state models to analyse the performance of both single and double-pass PV/T air collectors. The models yielded the temperature profiles of the glass cover, plates, and air stream while the mean plate temperature could be applied to evaluate the efficiency of the photovoltaic cells. Performance analysis showed that the double-pass photovoltaic thermal solar collector produces better performance than the single-pass module at a normal operational mass flow rate range. In addition, the thermal and combined thermal and electrical efficiencies increased when the packing factor (defined as the ratio of the PV cell area to absorber area) decreased; whereas the electrical efficiency of the PVs decreased slightly.

Sandnes and Rekstad [61] constructed a PV/T unit by using a polymer solar heat collector combined with single-crystal silicon PV cell. An analytical model derived from the Hottel–Whillier equations was used to simulate the temperature distribution and the performance of both the thermal and photovoltaic parts. The simulation results were in agreement with the experimental data. They found that pasting solar cells onto the absorbing surface would reduce the solar energy absorbed by the panel (about 10% of incident energy) due to lower optical absorption in the solar cells compared to the black absorber plate. Further, there is an increased heat transfer resistance at the surface of absorber and within the fluid which reduces the collector's heat removal factor, F_R. Moreover, they concluded that the solar cells' temperature is strongly related to the system (inlet fluid)'s temperature and also to the collectors' heat transport characteristics. The combined PV/T concept should therefore be associated with applications of sufficiently low temperature to give the desired cooling effect.

Tiwari and Sodha [62] developed a thermal model for an integrated photovoltaic and thermal solar collector (IPVTS) system and compared it with the model for a conventional solar water heater by Huang et al. [25]. Based on energy balance of each component of the IPVTS system, an analytical expression for the temperature of PV module and the water have been derived. The simulations predicted a daily primary-energy saving efficiency of around 58%, which was in good agreement with the experimental value (61.3%) obtained by Huang et al.

Dubey et al. [63] developed an analytical model that indicated the electrical efficiency of PV module with and without cooling flow as a function of climatic and PV's physical/operational parameters. The four different PV configurations i.e. case A (Glass to glass PV module with duct), case B (Glass to glass PV module without duct), case C (Glass to tedlar PV module with duct), case D (Glass to tedlar PV module without duct) were investigated. It was found that the glass to glass PV module with duct gives higher electrical efficiency and the higher outlet air temperature among the all four cases. The annual average efficiency of glass to glass type PV module with and without duct was reported 10.41% and 9.75% respectively.

Chow [64] developed an explicit dynamic model with seven nodes of a single-glazed flat-plate water-heating PV/T collector suitable for use in systems' dynamic simulation. This model, derived from the control-volume finite-difference formulation and incorporated with a transport relay subprogram, could provide information on transient performance, including the instantaneous thermal/electrical gains, their efficiencies, and thermal conditions of various components. Further to an extension of the nodal scheme to include multi-dimensional thermal conduction on PV and absorber plates, this model was able to perform complete energy analysis on the hybrid collector.

Cox and Raghuraman [65] explored several useful design features of air based flat-plate PV/T collectors in order to determine their effectiveness and interaction on the basis of a computer simulation. They found the air PV/T types are usually less efficient than the liquid ones due to low PV cell packing factor, low solar absorptance, high infrared emittance and low absorber to air heat transfer coefficient. Methods to tackle these drawbacks were mainly recommended on two major ways: increasing the solar absorptance and reducing the infrared emittance. The results showed that when the packing factor is greater than 65%, a selective absorber could actually reduce the thermal efficiency when used with a gridded-back cell. The optimum combination for an air PV/T module was suggested to consist of gridded-back PV cells, a non-selective secondary absorber, and a high-transmitting/low-emissive cover above the PV cells.

Grag and Agarwal [66] developed a simulation model to investigate the effect of the design and operational parameters of a hybrid PV/T air heating system on its performance. It was found that whether or not to use single and double glass covers in a PV/T air heating system largely depended on the its design temperatures as the extra glass cover might lead to the increased transmission losses and beyond some critical point the single-glass cover can collect more heat than double glass does. The parametric studies showed that the system efficiency increases with increase in collector length, mass flow rate and cell density, and decreases with increase in duct depth for both configurations. However, as material cost increases by increasing the number of glass covers, collector length, cell density, duct depth and mass flow rate, final selection of design parameters and operational variables of a PV/T system must be based on the cost-effectiveness of the system by minimizing the life cycle cost of the system.

Kalogirou [53] carried out the modelling and simulation of the performance of a hybrid PV/T solar water system by using TRNSYS, which is a transient simulation program with typical meteorological year (TMY) conditions for Nicosia, Cyprus. The PV system consisted of a series of PV panels, a battery bank and an inverter whereas the thermal system consisted of a hot water storage cylinder, a pump and a differential thermostat. The results showed that the hybrid system increases the mean annual efficiency of the PV solar water system from 2.8% to 7.7% and in addition covers 49% of the hot water needs in a house, thus increasing the mean annual efficiency to 31.7%. The life cycle savings of the system was calculated at Cy£790.00 and the pay-back time was 4.6 years.

Tripanagnostopoulos et al. [67] constructed an air-based PV/T solar collector which applied two low cost approaches to enhance heat transfer between the air flow and PV surface. A finned metal sheet was attained to the back wall of the air-channel to improve heat extraction from the PV modules. The experimental tests were carried out on the air-based PV/T system which used a 46 Wp rated commercial pc-Si PV module and has 0.4 m^2 of aperture area as the absorber plate. The results showed good agreement between predicted values and measured data. It is found that the induced mass flow rate and thermal efficiency decrease with increasing ambient (inlet) temperature and increase with increasing tilt angle for a given insulation level. The results also showed that the optimum channel depth occurs between 0.05 and 0.1 m for this system. This type of PV/T system was practical and cost effective, suitable for being integrated into the building with both heat and electrical demands.

Dubey et al. [24] designed and constructed a PV/T solar air heater, and studied its performance over different operational parameters under steady indoor conditions. Experimental

simulator consisted of three PV modules (mono-crystalline silicon solar cells) of glass to tedlar type, each rating at 75 Wp, has 0.45 m in width and 1.2 m in length and was mounted on a wooden duct. They found that the thermal, electrical and overall efficiency of the solar heater obtained at indoor condition was 42%, 8.4% and 50%, respectively. They also proposed an indoor standard test procedure for thermal and electrical testing of the PV/T collectors connected in series. It is concluded that this test procedure can be used by manufacturers for testing different types of PV modules in order to optimize its geometrical sizes.

Shahsavar and Ameri [68] designed and tested a direct-coupled PV/T air collector with and without glass cover at Kerman, Iran. In their study, a thin aluminium sheet suspended at the middle of air channel was used to increase the heat exchange area and consequently improve heat extraction from PV panels. This PV/T system was tested in natural forced convection conditions (with two, four and eight fans operating). Good agreement between the measured values and those calculated by the simulation model were achieved. It is concluded that there is an optimum number of fans for achieving maximum electrical efficiency. Also, results showed that setting glass cover on photovoltaic panels leads to an increase in thermal efficiency and decrease in electrical efficiency of the system.

Huang et al. [52] studied an integrated photovoltaic–thermal system (IPVTS) set-up. A commercial polycrystalline PV module was used for making a PV/T collector, which is part of the IPVTS configuration. The testing approach for conventional solar hot water heaters was used to evaluate the thermal performance rating of the IPVTS. The tested results showed that the solar PV/T collector made of a corrugated polycarbonate panel can obtain a primary-energy saving efficiency of about 61.3%, while the temperatures difference between the tank water the PV module was around 4 °C.

De Vries [69] and Zondag et al. [17,70] carried out testing of a PV/T solar boiler with a water storage tank in the Dutch and found that the covered sheet-and-tube system was the most promising PV/T concept for tap water heating. It is reported that the water-based PV/T system can provide more architectural uniformity, minimize the usage of space on roof, and achieve reduced payback period. This PV/T system could achieve annual average solar efficiencies of between 34% and 39% for the covered designs, and 24% for the uncovered design.

Chow et al. [71] illustrated an experimental study into a combined centralized photovoltaic and hot water collector wall system that can serve as the water pre-heater. The collectors were mounted at vertical facades and different operating modes were implemented for different seasons. They found that natural water circulation was preferable to the forced circulation in this hybrid solar collector system. The thermal efficiency was reported 38.9% at zero reduced temperature, and the corresponding electricity conversion efficiency was 8.56%, during the late summer in Hong Kong. With the PV/T wall, the space thermal loads can be significantly reduced both in summer and winter, leading to substantial energy savings.

Zhao et al. [21] designed two experimental prototypes by integrating the flat-plate heat pipe with the mono-ci PV cells at the effective area of 0.0625 m^2 while the surplus heat was taken away respectively via the natural air flow and passive water circulation. In comparison with the solely PV system, the PV/T modules were found to be able to achieve the enhanced electrical efficiencies of 2.6% and 3%, and the reduced cell temperatures of 4.7 and 8 °C respectively for air and water based conditions.

Ji et al. [72] developed a novel solar PV/T heat pump (PV/T-SAHP) system that combined a Rankine refrigeration cycle with a PV/T solar collector. A dynamic model for the PV evaporator was established using the distributed parameter approach to investigate the effect of the refrigerant parameters (e.g. pressure, temperature, vapour quality and enthalpy) onto the system's solar efficiencies, and study the temperature distribution across the evaporator channels. The results indicated that the PV electrical efficiency and evaporator thermal efficiency are around 12% and 50% respectively during the testing period in Hefei, China.

On the basis of the above work, Ji et al. [26] carried out the testing of the system under a range of operational conditions. The results indicated that the PV-SAHP system has a higher coefficient of performance (COP) than the conventional heat pump system and the PV's electrical efficiency is also higher. The COP of the heat pump was able to achieve 10.4 while the average COP value of the traditional heat pumps was around 5.4. The average PV solar efficiency was around 13.4%. The highest overall coefficient of performance (COP – peak), taking into account the performance of PVs and evaporators, was around 16.1.

Zhao et al. [14] designed a novel PV/e roof module to act as the roof element, electricity generator and the evaporator of a heat pump system. The energy profiles and system operating conditions were analysed and temperature distribution across the module layers was simulated. This study indicated that the combined system should operate at 10 °C of evaporation and 60 °C of condensation temperature. Borosilicate as a top cover has better thermal performance than polycarbonate and glass; while the mono-crystalline photovoltaic cells are of higher electrical efficiency over the poly-crystalline and thin-films. Under a typical Nottingham (UK) operating condition, the modules would achieve 55% of thermal efficiency and 19% of electrical efficiency, while the module based heat pump system would have an overall efficiency of above 70%. It was also addressed that the integration of the PV cells and evaporation coil into a prefabricated roof would lead to large saving in both capital and running costs over separate arrangements of PV, heat pump and roof structure.

Apart from the above reports, many other works in this subject have been found from the literature study and a few more examples of these are briefed as below.

For air-based PV/T, Komp and Reeser [73] reported on the design and installation of a stationary concentrating glazed roof-integrated PV-air collector for an off-grid dwelling. The hybrid collector is equipped with fins to enhance the heat transfer between the PV cells and air; the air was then drawn into the house using a fan in winter and by natural convection in summer. Fudholi et al. [74] indicated that drying up agricultural and marine products is one of the most attractive and cost effective applications for solar PV/T technology. Takashima [75] concluded that the surface temperature of the PV panels could be reduced when air gap was remained above the PV to form a thermal collector. Moshtegh and Sandbergy [76,77] numerically and experimentally studied the performance of air flow induced by buoyancy and heat transfer within a vertical channel heated from the PV side wall. The study reported that the induced velocity increases the heat flux non-uniformly inside the duct and its impact depends on the sizes and geometry of the air exit. Bhargvaa [78] and Parkash [79] studied the performance single-pass PV/T air collector using a computer model and analysed the influence of air mass flow rate, depth of air channel and packing factor to the system's overall efficiency. Sopian et al. [60] analysed the performance of both single and double-pass PV/T air collectors using steady state computer models. The results showed that double-pass PV/T air collectors have higher efficiencies than the single-pass ones but its capital cost is a bit higher. Kelly [80] and Tripanagnostopoulos [81] suggested several possible approaches to enhance the cooling effect, such as modifying channel geometries to create more turbulence for flows. Tiwari and Sodha [82] indicated that the glazed air PV/T collectors have higher thermal efficiency than the paralleled unglazed ones, especially at low temperature conditions where the double glazing cover was found to be superior to the single glazing cover [83]. On the other hand, the glazing cover would slightly reduce the overall performance

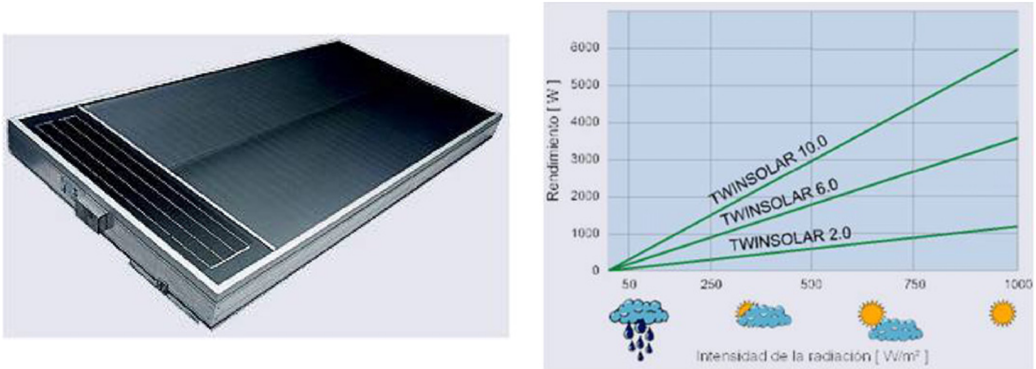

Fig. 13. The 'TWINSOLAR' application and its performance curve [90].

of the collector owing to unavoidable solar reflection occurring on the cover.

For water-based PV/T, Agarwal and Grag [84,66] designed the prototypes of thermisyphonic and flat-plate PV/T water heaters. Bergene and Lovvik [59] then conducted an energy transfer study on PV/T water system composed of flat-plate solar collector and PV cells, which indicated that an overall efficiency of 60–80% can be achieved. It is found that the proposed system could be used to preheat the domestic hot water. More recently, Zondag et al. [17] classified the water-based PV/T collectors into four major types namely sheet-and-tube collectors, channel collectors, free-flow collectors, and two absorber collectors. Chow et al. [71] suggested that implementing the water flow channels beneath the transparent PV module may be a good choice to achieve enhanced solar efficiency. However, the single-glazing sheet-and-tube hybrid PV/T collector is regarded as the most promising design as it has high overall efficiency and is easy to construct. Kalogirou and Tripanagnostopoulos [11,53] simulated a PV/T water supply and storage system and found that the economic viability of PV/T water system was much better than the air-based type. Elswijk et al. [85] installed large PV/T arrays on residential buildings and reported that the use of PV/T would save around 38% in roof area, relative to a side-by-side system of PV and solar thermal. Ji et al. [86] studied a facade integrated PV/T collector for residential building in Hong Kong. The annual thermal efficiencies were found to be around 48% for the thin film silicon and 43% for the crystalline silicon case respectively. In addition, the building intergraded system was able to reduce the cooling requirements of the building substantially due to the reduced heat absorption by walls.

For refrigerant/heat-pipe-based PV/T, Nishikawa et al. [87] studied a PV/T heat pump system using R22 as the refrigerant. When the PVs were effectively cooled, the system could achieve higher COP than a conventional heat pump could. Ito et al. [88] worked on a similar PV/T heat pump and found that when the condensation temperature was set at 40 °C, the COP of heat pump could achieve as high as 6.0. Further, Ito et al. [89] analysed the effect of a few physical parameters e.g. collector area, width, length and thickness of the collector plate to the system's solar efficiency and COP. Zhao et al. [19–21] initiated a PV/flat plate heat pipe with micro-channel arrays inside to produce electricity and hot air/water simultaneously, which is detailed in Fig. 11. Further, Qian et al. [22,23] invented a building integrated photovoltaic/thermal system using oscillating heat pipe for the combined heat and power generation using solar energy. This type of system was addressed in Fig. 12.

3.2. Practical application of the PV/T technologies

Although the PV/T technology is in the start-up stage, some commercial products or engineering projects related to PV/T application can still be found in practice. A number of PV/T practical works are addressed as follow:

'Grammer Solar GmbH' in Germany has developed an air-based PV/T solar collector titled 'TWINSOLAR' which is designed to preheat ventilation air in buildings and has the absorber area of between 1.3 and 12.5 m^2. The modules can be assembled vertically or horizontally, on the roof or on the south, southeast, or southwest facing facades. It is observed that at maximum solar radiation of 700 W/m^2, the air temperature rose to 40 °C and nearly 70% of the solar incident energy was converted into thermal energy and transported into the building, as shown in Fig. 13 [90].

In Denmark, the SolarVenti units are mainly used for providing ventilation and supplementary heating and assisting in air dehumidification. The larger capacity SolarVenti models have substantial thermal energy output and can drive significant amount of air due to the effect of the buoyancy force. The thermal energy is captured directly from solar radiation across the spectrum, can be used to supplement the existing space heating system in any domestic or commercial building. Table 4 provides the energy outputs for different SolarVenti models [91].

The Canadian 'Conserval Engineering Inc' provides the SolarWall and the rooftop SolarDuct products. The SolarWall is a proprietary solar air heating system that can heat up building using ventilation air, and also be amounted on walls or roofs for various purposes including heating up buildings and running agricultural and manufacturing drying-up process. The SolarWall is a PV/T combined system that has significantly lower payback period than a PV system. It can produce up to 400% more usable energy than a solely PV system. The SolarDuct PV/T is a modular rooftop system with total operating efficiency of above 50% where the thermal panels have doubled the output from the PV racking system [92]. Fig. 14 indicates the product series available in this company.

The Dutch based 'PVTWINS' developed the PV/T water heating products for niche market, as shown in Fig. 15 [93]. The PV/T water collectors can be used in individual and collective domestic hot water systems. This PV/T type can achieve a temperature as high as 90 °C. The electrical yield is measured with 125 Wp/m^2 and the thermal yield is about 1.2 GJ/m^2 year. The PV/T collectors have

Table 4
Energy output of different Solarventi models [91].

Model	Air volume (m^3/h)	Temperature increase (°C)	Max output kW (/h)	Max output kW per year (1000 h sun)
SV14	60	~30	0.6	600
SV30	120	~40	1.6	1600
SV30H	100	~40	1.3	1300

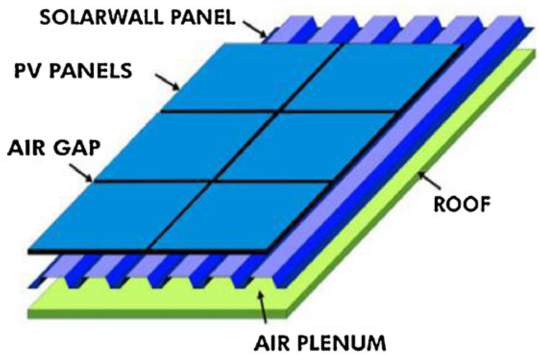

Fig. 14. The solar air PV/T products of 'Conserval Engineering' company [92].

Fig. 15. PV/T liquid collector – PVTWIN from 'PVTWINS' company [93].

three available sizes e.g. 1800 mm × 1800 mm, 900 mm × 5600 mm and 1800 mm × 2400 mm, and are suitable for being integrated into tilted or flat roofs using a common connection method.

The Israel based 'Millennium Electric Ltd' has developed a MULTI SOLAR PV/T System that enables conversion of solar energy into thermal and electrical energy simultaneously using a single hybrid system, as shown in Fig. 16 [94]. The Multi Solar System is made of facade/roof tile-like panels which behave as a "living" skin around the building allowing the flow of water to cool the PV cells, capture heat and store it in an insulated tank, thus enabling heat control of the living environment. The system can generate 30% higher PV efficiency in production of electricity for domestic use.

In terms of PV/T concentrators, three major manufacturers in the world namely Absolicon in Sweden, Menova Energy in Canada and HelioDynamics in the UK involved with this kind of business. 'Absolicon' produced an X10 PV/T commercial heat and power system as shown in Fig. 17 [95]. The system consists of a cylinder-parabolic reflector that concentrates ten times the solar light onto the receiver. It is also equipped with the latest generation of photovoltaic technology and a solar tracking system using special electrical custom-designed high quality linear actuators. The aim is to rotate the X10 concentrator to allow the sunlight to be focused onto the cells all the time. The tracking system has a built-in program that can automatically protect the photovoltaic cells from being overheated or from storms. If the temperature exceeds a certain value, the X10 automatically turns the receiver away from the sun.

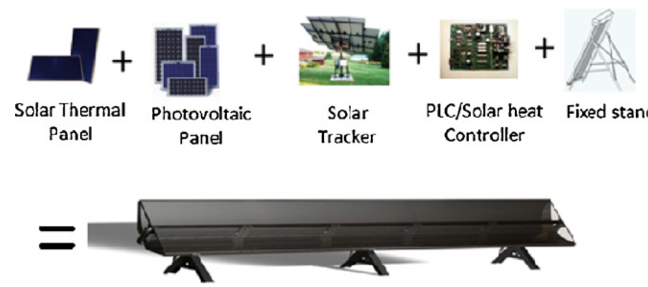

Fig. 17. 'X10' PV/T system from 'Absolicon' company [95].

'Menova Energy' provides the Power-spar PV/T concentrator for use in domestic application, as shown in Fig. 18 [96]. The Power-Spar model has been specifically engineered to provide enhanced performance even when being exposed to extreme winter temperature.

'HelioDynamics' provides a tracking, modular PV/T concentrator namely 'Harmony HD 211', as shown in Fig. 19 [96]. It is designed for being mounted on the flat and sloping roofs or pole-mounted over parking areas at the mid-latitudes (20–40°).

The ventilated PV with heat recovery is a type of recently emerged PV/T air collector system. The system is designated to provide solutions for ventilating the PV cells to maximise the electrical

Fig. 16. 'MULTI SOLAR' PV/T System from 'Millennium Electric' [94].

Fig. 18. 'Power-spar' from 'Menova Energy' company [96].

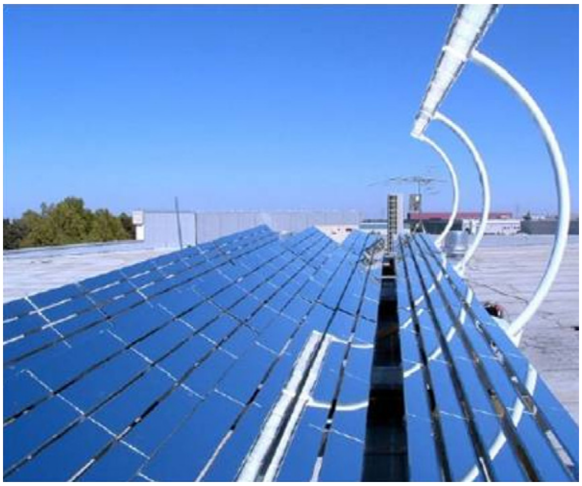

Fig. 19. 'Harmony HD211' from 'HelioDynamics' company [96].

yield and utilizing the PV heat for preheating the ventilation air. Standardised products for this purpose have been manufactured in Secco Sistemi, an Italian PV manufacturers, as shown in Fig. 20 [96]. This type of system has been used in various engineering projects including the Fiat Research Centre, Imagina Studio in Barcelona and the Professional Training Centre in Casargo.

3.3. Analyses of the review works

Works related to PV/T technology were found very substantial, and the above case-to-case statement may be too scattered to capture the main sense of the research works in this subject. To allow clear justification of the research progress and engineering practice in PV/T, the above works are further analysed from two angles: (1) system type; (2) research methodology. These are summarised as follows:

3.3.1. Analyses of the research works in terms of system types and their performance

In terms of the system types concerned, the research can fall into four categories, namely (1) air-based PV/T; (2) water-based PV/T; (3) refrigerant-based PV/T; and (4) heat-pipe-based PV/T. Of these systems, air and water based types are relatively mature technologies and have already been widely used in the practical projects; while the refrigerant and heat-pipe based systems are still in research/laboratory stage and some technical/economic barriers still remain that prohibited their wide application.

Fig. 20. Ventilated PV with heat recovery – TIS from 'Secco Sistemi' [96].

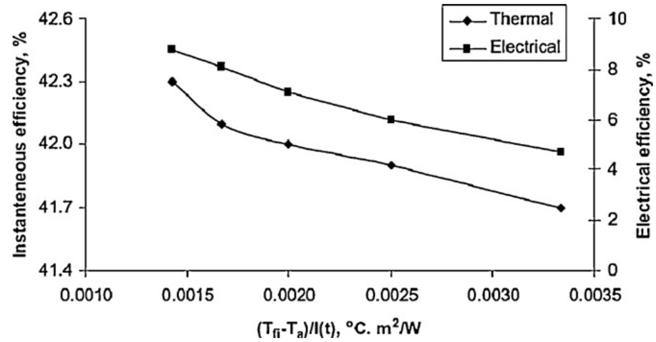

Fig. 21. Variation of instantaneous and electrical efficiencies with external and operating conditions [24].

3.3.1.1. Air-based PV/T. Air-based PV/T is one of the most commonly used PV/T technologies and has been developed into commercial units or/and used in many engineering practices. This type of system usually comprises of (1) commercial laminated PV modules; (2) special designed air flow channels/ducts; (3) active fans; (4) air handling unit or air/air heat exchangers [90,92], and its solar efficiency behaves as the function of geometrical parameters and external climatic conditions. The most favourite unit configuration and material are the integrated frameset of aluminium absorber and lamina separated channels with either presence or absence of built-in commercial PV cells [90]. A diagram showing the relation between the solar thermal and electrical efficiencies and the operational parameters is presented in Fig. 21 [24].

In overall, a typical air-based PV/T type can achieve maximum electrical efficiency of around 8% and thermal efficiency of around 39% [24]. Its performance is largely dependent on the air flow speed and temperature. Researches related to this type of PV/T system usually focus on (i) studying the more favourite air flow patterns e.g., buoyancy-driven and forced flow, (ii) determining the optimised channel geometry and sizes to enable creating effective turbulence within the channels, and (iii) selecting proper glazing modes e.g. uncovered or covering with single/double glass. The major problem with the air-based system lies in its relatively poor heat removal effectiveness owing to the low density, specific heat capacity and thermal conductivity of the air.

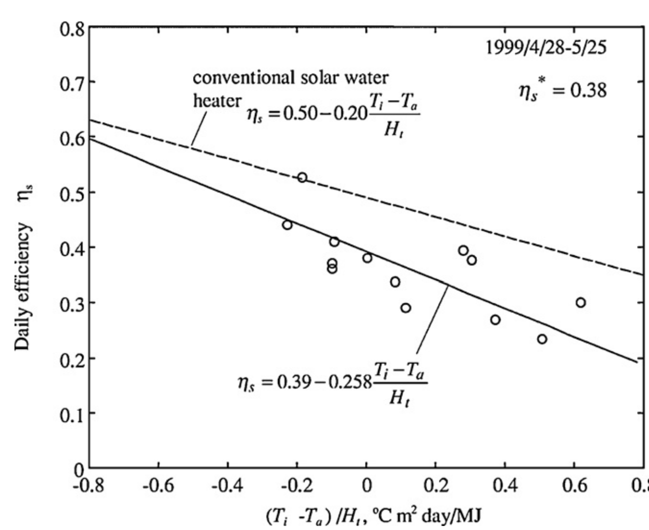

Fig. 22. Variation of daily test efficiency with external and operating conditions [25].

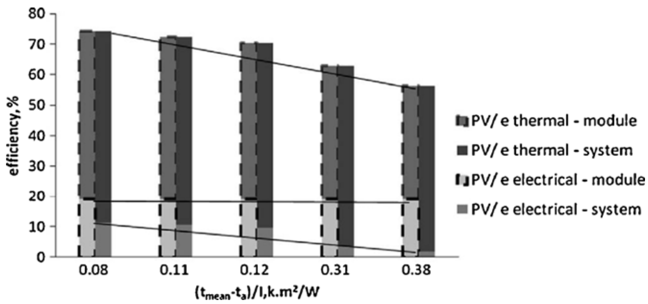

Fig. 23. Variation of module and system efficiencies with external and operating conditions [14].

3.3.1.2. Water-based PV/T. Water-based PV/T is second most popular PV cooling approach, and has gained growing use in practice over the recent years. Numerous commercial products have emerged on markets and most impressive examples include 'PVTWIN' series products by PVTWINS, and 'MULTI SOLAR' by Millennium Electric. The performance of the water-based PV/T technology is usually indicated by its electrical and thermal efficiencies which are found to vary with the water temperature, flow rate, water flow channel geometry and sizes, PV type, as well as external climatic condition. The most favourite unit configuration and material are the PV/T-laminate with the single-glazing and sheet-and-tube absorber in an aluminium frame and insulation on the back side, which is regarded as the most promising design as it has relatively high overall efficiency and is easy to construct [93]. A diagram showing correlation between solar efficiencies and the operational parameters is presented in Fig. 22 [25], which is established on the basis of the fixed geometrical conditions and PV type.

In overall, a typical water-based PV/T type can achieve maximum electrical efficiency of around 9.5% and thermal efficiency of around 50% [25]. Its performance is largely dependent upon water temperature, flow rate, water flow channel geometry and sizes, PV type, as well as external climatic condition. Researches related to water-based PV/T system usually focus on (i) determining appropriate water flow velocity and temperature, (ii) optimising water flow channel's geometry and sizes, and (iii) suggesting the configuration of the integrated PV/T panels including covers, PV cells and their connections, etc.

Compared to the air-based system, the water-based system could improve the electrical efficency of the PVs and increase the solar heat energy utilization. However, the scope for improvement is severly limited due to some inherent technical difficulties. Firstly, the water-based system remains continuously rising temperature and falling solar efficiency due to variation of the water temperature over the operating period and at high water temperature operation, the heat removal effectiveness becomes very poor; and secondly, additional heating prior to the heat devices (to achieve required water temperature) would increase the complexity of the system and reduce its efficiency. Further, the freezing may be a problem when the system operates at a cold climate region.

3.3.1.3. Refrigerant-based PV/T. Refrigerant-based PV/T is a recently emerging technology and research into this subject showed that the technology could significantly improve the solar utilization rate over the air- and water-based systems and therefore has potential to replace the former two systems in the near future. The system usually operates in conjunction with a heat pump, and its performance is justified by the electrical and thermal efficiencies of the PV/T modules and the COP of the PV/T heat pump system. These parameters (efficiencies and COP) vary with the flow rate of the refrigerant, its pre-set evaporation and condensation temperature/pressure, flow channels, geometrical sizes, PV type and external climatic conditions. The most favourite configuration and material are the solar cell encapsulation laminated on the front surface of an aluminium-alloy base plate, followed by the serpentine copper coils tightly positioned in the Ω-shaped grooves of another aluminium fin plate, together with insulation and outside frame forming up a unitary evaporator module [26,72]. A diagram showing interrelation between solar efficiencies and the operational parameters is presented in Fig. 23 [14], which is developed on the basis of the fixed geometrical conditions and PV type.

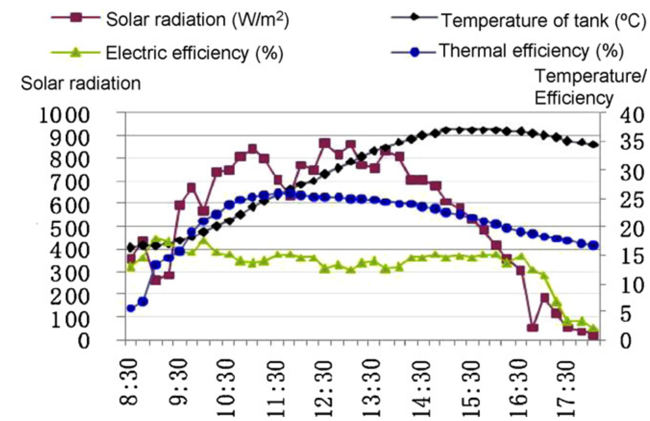

Fig. 24. Variation of daily test efficiency with running time [20].

In overall, a typical refrigerant-based PV/T type can achieve maximum electrical efficiency of around 10% and thermal efficiency of around 65% [26]. Researches related to refrigerant-based PV/T system usually focus on (i) determining appropriate refrigerant type, flow rate, evaporation/condensation temperature and pressure, (ii) optimising refrigerant flow channel's geometrical shape and sizes, and (iii) suggesting the configuration of the integrated PV/T and heat pump including panel configuration e.g. covers, PV cells and combination between PVs and refrigerant channels, and connection between the PV/T panels and the heat pump.

Compared to the air/water-based systems, the refrigerant-based system could significantly improve the electrical efficency of the PVs and increase the solar heat energy utilization. This initiative represents a step forward in BIPV cooling technology but its practicality faces many challenges: the refrigerant piping cycle needs a perfect seal in order to maintain its higher (positive) or lower (negative) pressures at different sections and prevent air being sucked into the system during operation, which is very difficult to achieve owing to the numerous joints in existence. There is also high risk of refrigerant leakage and achieving balanced refrigerant distribution across the multiple coils installed at a large PV panel area is technically difficult.

3.3.1.4. Heat-pipe-based PV/T. Heat-pipe-based PV/T is also a relatively new technology and researches into this subject were found very limited. Up-to-date, flat-plate and oscillating heat pipes were studied for potential use in PV cooling and the results indicated the heat pipes may have potential to overcome the problems existing in refrigerant-based system, e.g. possible leakage of refrigerant, unbalanced distribution of refrigerant flow and difficulty in retaining pressurisation or depressurisation states in different parts of the system.

This system usually operates in conjunction with a heat pump or a heat cycle, and its performance is justified by the electrical and thermal efficiencies of the PV/T modules and the heat pipe heat transport capacity. These performance parameters (efficiencies and heat transport capacity) vary with the structure/material and vacuum degree of the heat pipe, type of the heat pipe fluid, temperature

and flow rate of the secondary fluid, PV type and external climatic conditions. The most favourite unit configuration and material are the commercial PV wafers attached on the aluminium flat-plate heat pipes while its headers locate in a water manifold and all the unit joints are connected with thermally conductive silicon grease [20]. A diagram showing interrelation between solar efficiencies and the running time is presented in Fig. 24, which is developed on the basis of the fixed geometrical conditions and PV type.

In overall, a typical heat-pipe-based PV/T type [20] can achieve maximum electrical efficiency of around 10% and thermal efficiency of around 58%. Researches related to heat-pipe-based PV/T system usually focus on (i) determining appropriate heat pipe structure/material and vacuum degree, heat pipe fluid type and volume, flow rate and inlet temperature of the secondary fluid, (ii) optimising heat pipes' geometrical shape sizes and (iii) suggesting the configuration of the integrated PV/T and heat-pipe and other heat removing system including panel configuration e.g. covers, PV cells and combination between PVs and heat pipes, and connection between PV/T panels and secondary fluid cycle.

Compared to the refirgerant-based system, the heat-pipe-based system could achieve an instant eqivalent performance if the heat pipes operate at an adequate temperature. This system may overcome the difficulties exisitng in the refrigerant-based system and become the next generation technology for removing heat from PVs and effectively utilizing this part of heat. However, this type of system also found some disadvantages that require further resolutions, e.g., high cost of the heat pipes and good control of the heat pipe performance.

3.3.2. Analyses of the research works in terms of research methodology

In terms of research methodology used, the research works can be classified as (i) theoretical analyses and computer modelling; (ii) experimental study; (iii) combined modelling and experimental study; (iv) economic and environmental analyses; and (v) demonstration of the technology and the associated feasibility study.

3.3.2.1. Theoretical analyses and computer modelling. Many theoretical works have been carried out to study performance of the PV/T modules and the associated heat and power system. These works were dedicated to (1) reveal the temperature distribution across the various layers of the PV/T modules and energy (heat and power) conversion mechanism; (2) optimise the structural/geometrical parameters of the PV/T modules including the constitution, connection, geometrical shape and sizes; and (3) recommend the favourite operational conditions e.g. fluid flow rate, temperature, pressure, etc.

Theoretical works done so far cover (1) simple analytical model addressing heat transfer and heat balance across different parts of the PV/T modules and modules-based energy system [56,57]; (2) one-dimensional thermal model derived from the conventional solar thermal flat-plate collectors with inclusion of PV electrical yields [58–61]; (3) two/three-dimensional model addressing the energy transfer and distribution across the PV/T modules and the modules-based energy system [70,72]; (4) transient energy model simulating the dynamic characteristics of the PV/T modules and modules-based energy system [64,79]; and (5) energy and exergy analytical models to study the overall energy utilization performance of the integrated systems [51,97].

In summary, established theoretical models have sufficient breadth and depth to reveal the nature of the technology and predict its performance, and further optimise the system's configuration and suggest the favourite operational conditions. The further work on this methodology category may fall into the system's dynamic performance study under long term operational conditions e.g. seasonally and annually scheme.

3.3.2.2. Experimental and combined modelling/experimental study. Experimental study, running from the individual modules to the whole system scheme, measured various operational parameters including temperature, flow, heat and power conversion rates. The aims are to (1) reveal the real performance of the PV/T components and the whole system under the specified operational conditions; (2) examine the reliability and accuracy of the established computer model and provide the clues for further tuning and modification to the model; and (3) establish the correlation between the theoretical analysis and practical application.

Experimental and combined modelling/experimental works done so far cover (1) PV electrical efficiency and its relevance with various operational parameters, particularly with PV cells temperature [25,54,62]; (2) heat removal effectiveness of the various cooling mediums e.g. air, water, refrigerant and heat pipe fluids [20,24,26,71]; (3) temperature and fluid flow characteristics of the PV/T modules and modules-based energy system [98,99]; (4) thermal and electrical conversation rates of the PV/T modules and the modules-based energy system [82,100]; (5) comparison between the modelling results and experimental data and error analyses [68,72]; and (6) validation, accuracy analyses, tuning and modification of the computer model [62].

In summary, experiment and combined modelling/experimental works done are also very substantial, and have found good agreement with most theoretical results. These works also provided the feasible approach to lead the theoretical findings towards the practical application. The further work may lie in the measurement of the system's dynamic performance under long term operational conditions e.g. seasonal and annual scheme.

3.3.2.3. Economic and environmental analyses. Some research works focused on economic and environmental analyses of the PV/T technology by comparing its performance against those for individually arranged PV and solar thermal technologies. In terms of economic issues, simple payback time and life cycle cost were addressed taking into account primary fossil fuel energy saving and increase in capital cost and maintenance cost needed during the system operation. In terms of environmental issues, energy and exergy efficiencies of the system, Energy Payback Time and Greenhouse-gas Payback Time were calculated and used as the indexes to justify the benefits of the system in terms of the capacity of carbon emission cut.

Works related to economic and environmental analyses cover (1) PV/T energy saving potential, its cost augment, estimated payback time and life cycle cost saving [54]; (2) PV/T Energy Payback Time and Greenhouse-gas Payback Time and their relevance with the system's energy and exergy efficiencies [54]; and (3) comparison among different PV/T configurations, PV alone, solar thermal alone and separately laid PV and solar thermal arrangements [13,14].

In summary, economic and environmental analyses works done so far are adequate to indicate the performance of the PV/T technology in terms of its economic and carbon benefits. The further work may be extended to long term (seasonal and annual) analyses of the system's performance by taking into account the influence of the climatic conditions to the system performance.

3.3.2.4. Demonstration of the PV/T technology and the associated feasibility study. Although PV/T technology has been used in many practical projects, there are very little report found by literature search to focus on assessing the long term performance of PV/T technology under real climatic conditions and consequently,

feasibility of the system used in practical projects as a long term measures has not yet been fully studied. This may be the area to be further explored in the near future in relation to the PV/T technology development.

3.3.3. Conclusive remarks of the review works

To summarise, the established researches so far in PV/T technology are very substantial and have clear focuses on (1) reveal the nature of the energy transfer and conversation occurring in the PV/T modules and modules-based system; (2) identify the favourite the system type; (3) optimise the structural/geometrical parameters of the systems and suggest the appropriate operational conditions; (4) build the link between the theoretical analyses and practical application; and (5) analyse the economic and environmental benefits of the PV/T systems and study their feasibility for long term operation. All these efforts contribute to a single purpose: to create as much energy efficient PV/T system as possible at the least possible cost and simplest structure.

4. Opportunities for further works

Although significant works have been completed, there are still obvious opportunities to catch up to further develop this technology, which are outlined as below:

4.1. Developing new feasible, economic and energy efficient system types

The aforementioned system types were found their own disadvantages that have prohibited wide application of these systems in practice. The opportunity to develop new system types to replace the existing systems still remains open and very recently, a new method to remove PV heat and utilize this part of heat was proposed [101]. In this study, the emulsified PCM slurry, as a latent heat convertor/conveyor, will be brought into the PV/T system to remove the PV heat, and this part of heat will be used to provide space heating, hot water supply and ventilation of the buildings, by running a combined operation of the PV/T modules, a heat pump, a heat storage and a slurry-to-air heat exchanger. This will open up a new way to develop a more feasible, economic and energy efficient PV/T system; however, the claimed advantages of the system will need further validation through in-depth theoretical and experimental studies. Apart from this, other types of PV/T configurations are also open to exploration.

4.2. Optimising the structural/geometrical parameters of the existing PV/T configurations to enhance their energy performance

Of the four existing PV/T system types, air- or water- based types are technically and commercially very mature and have no obvious room to improve their performance. The refrigerant-based type is still in the research stage and space still remains to improve its performance through the optimal study of the structural/geometrical parameters of this type of the PV/T module. The key issue is to find a route to overcome the difficulties remaining in the existing refrigerant PV/T type, i.e., potential refrigerant leakage, unbalance refrigerant distribution and challenges in retaining pressurisation and depressurisation conditions at different parts of the system. Heat-pipe-based system is also in the start-up stage and remains large space to develop the optimised system configurations. The low cost flexible loop heat pipes with built-in capillary would be a good choice to replace the existing parallel laid heat pipes and have potential to reduce the cost of the system and build up the excellent heat transfer between PVs and secondary fluid [102]. This work is currently being undertaken by the authors as part work of an industrial funded research project.

4.3. Studying long term dynamic performance of the PV/T systems under real climatic conditions

Steady state performance of various PV/T systems has been theoretically and experimentally studied as the result of the previous researches, and no obvious space could be seen to further develop the research work in this regard. However, dynamic performance of the PV/T systems under real climatic conditions has not yet been fully examined, particularly at long term (seasonal or annual) scheme. This work remains certain challenges as several uncertain factors e.g. influence of irregular variation of the solar radiation, ambient temperature and wind speed onto the system performance, are difficult to predict. Combined theoretical and experimental study may enable a solution to the problem.

4.4. Demonstration of the system operation in real building and feasibility study

It is known that PV/T technology has been used in many practical projects. However, there is little report found by literature search that focused on assessment of the system's performance under real climatic conditions. Research could be developed from this angle to develop, install and monitor the PV/T systems in real buildings. This will allow assessment of the real performance of the system including reliability and commercialisation potential. Further, feasibility of the system used in real buildings could be examined. This work could possibly chase up the research outcomes to commercial application.

4.5. Economic and environmental analyses

Current works on economic and environmental analyses of the PV/T system have been conducted on laboratory and computer modelling bases. Further work could be extended in this regard to take into account effect of the climatic conditions to the system's performance through long term measurement.

5. Conclusions

A review into R&D works and practical application of the recently emerging PV/T technology has been carried out. The results of the work help understand the current status of the PV/T technical development, identify the potential difficulties and barriers remaining in this sector, develop the potential research topics/directions to further improve the performance of the PV/T, establish the associated strategic plans, standards and regulations related to PV/T design and installation, and promote its market exploitation throughout the world.

PV/T is a technology combining PVs and solar thermal components into a single module to enhance the solar conversion efficiency of the system and make economic use of the space. The dual functions of the PV/T result in a higher overall solar conversion rate than that of sole PV and solar thermal collector. PV/T modules are architecturally adaptable and have the potential to develop into a range of standardized and aesthetically appealing commercial products. Its market potential is expected to be high compared to the individual PV and solar thermal systems due to its obvious benefits over the independent systems.

PV/T modules could have very different structures. In terms of coolants used, currently available PV/T configurations could be classified as air, water, refrigerant and heat-pipe based types. Technical performance of a PV/T system is usually evaluated using energy

and exergy efficiencies; whereas its economic performance is measured with Life Cycle Cost (LCC) and Cost Payback Time (CPT), and the environmental benefit justified by Energy Payback Time (EPBT) and Greenhouse Payback Time (GPBT).

Air-based PV/T is one of the most commonly used PV/T technologies and has been developed into commercial units and used in many engineering practices. This type of system can achieve maximum electrical efficiency of around 8% and thermal efficiency of around 39%, and its performance is largely dependent on the air flow speed and temperature. The major problem with the air-based system lies in its relatively poor heat removal effectiveness owing to the low density, specific heat capacity and thermal conductivity of the air.

Water-based PV/T is also a very popular technology and has gained growing application in practical projects. This type of system can achieve maximum electrical efficiency of around 9.5% and thermal efficiency of about 50%, and its performance is largely dependent upon water temperature and flow rate, water flow channels' geometrical shape and sizes. Compared to the air-based system, the water-based system could improve the electrical efficiency of the PVs and increase the solar thermal energy utilization. However, the scope for improvement is limited by a few its inherent technical difficulties, namely, arising water temperature during the operation and complex system layout.

Refrigerant-based PV/T could significantly improve the solar utilization rate over the air- and water- based systems and therefore has potential to replace the former two systems in the near future. The system usually operates in conjunction with a heat pump, and its performance is largely dependent upon the type and thermal/physical properties of the refrigerant used, and structural/geometrical parameters of refrigerant flow channels. The refrigerant-based PV/T can achieve maximum electrical efficiency of around 10% and thermal efficiency of around 65%. This system represents a step forward in BIPV cooling technology but its practicality faces several challenges, namely, potential refrigerant leakage, unbalanced refrigerant distribution across the panel coils, as well as difficulty in pressure maintenance over the operation duration.

Heat-pipe-based PV/T is also a relatively new technology and its operation is often in conjunction with a heat pump or a heat cycle. A heat-pipe-based PV/T system can achieve maximum electrical efficiency of around 10% and thermal efficiency of nearly 58%, and its performance is largely dependent upon the structure/material and vacuum degree of the heat pipe, type of the heat pipe fluid, temperature and flow rate of the secondary fluid. This system may overcome the difficulties exisitng in the refrigerant-based system and become the next generation technology for removing heat from PVs and effectively utilizing this part of heat. However, this type of system also found some disadvantages that require further resolutions, e.g., high cost of the heat pipes and effective control of the heat pipe performance.

The researches established on PV/T technology were very substantial and mainly focused on (1) revealing the nature of the energy transfer and conversation occurring in the PV/T modules and modules-based system; (2) identifying the favourite the system type; (3) optimising the structural/geometrical parameters of the system configuration and suggest the appropriate operational conditions; (4) building the link between the theoretical analyses and practical application; and (5) analysing the economic, environmental benefits of the PV/T systems and evaluating their feasibility for long term operation. All these efforts aimed to create as much energy efficient PV/T system as possible at the least possible cost and simplest structure.

Although significant works have been completed in PV/T study, there are still some opportunities existing for further developing this technology, including (1) developing new feasible, economic and energy efficient systems such as PCM-slurry-based PV/T; (2) optimising the structural/geometrical parameters of the existing PV/T configurations; (3) studying long term dynamic performance of the PV/T systems; (4) demonstration of the PV/T systems in real buildings and feasibility study; and (5) advanced economic and environmental analyses taking into account effect of the climatic conditions onto the performance of the system through long term measurement.

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